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Active structural health monitoring of composite plates and sandwiches

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Abstract

The aim of presented work is to design, assemble and test a functional system, that is able to reveal damage from impact loading. This is done by monitoring of change of spectral characteristics on a damaged structure that is caused by change of mechanical properties of material or by change of structure's geometry. Excitation and monitoring of structures was done using piezoelectric patches. Unidirectional composite plate was tested for eigenfrequencies using chirp signal. The eigenfrequencies were compared to results from experiments with an impact hammer and consequently with results from finite element method. Same method of finding eigenfrequencies was used on a different unidirectional composite specimen. Series of impacts were performed. Spectrum of eigenfrequencies was measured on undamaged plate and then after each impact. Measurements of the plate with different level of damage were compared. Following experiments were performed on sandwich materials where more different failures may happen. Set of sandwich beams (cut out from one plate made of two outer composite layers and a foam core) was investigated and subjected to several impacts. Several samples were impacted in the same manner to get comparable results. The impacts were performed with growing impact energy.

Keywords: piezoelectric, structural health monitoring, composite, chirp

1. Introduction

As the demands on the ratio of stiffness and strength to weight of structures are rising, light-weight structures are nowadays necessary components in modern state-of-the-art products in all sorts of industries. Light modern superalloys are expensive and like conventional materials can sustain the same loading in all directions, even though the main loading may take effect in only one direction. To provide cheaper light-weight structure, new approach has to be applied. One of the solutions is usage of composite materials. Composite materials are mostly man-made materials made from one or more hard non-continuous component materials imbedded in a less hard continuous material with significantly different physical or chemical properties. Due to wide variety of materials to combine, their ratio or orientation of reinforcement, the diversity of composite materials is endless. As composite materials are generally not isotropic, prediction of failure of material is more complicated then for isotropic materials (fiber and matrix failure as well as delamination may occur). This results in more frequent check-ups or overdesigning of the whole part. Instead of frequent human check-ups an automated, computer based [1] operated system has been developed. The process of implementing a damage identification strategy is called structural health monitoring (SHM). This process consists of observation of a structure or mechanical system over a period of time using time-spaced measurements of specific features.

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Results from these measurements are analyzed to determine the current state of health. This is used in aircraft industry [7] as well as in civil engineering [2].

One of the possible monitoring devices are patches made out of piezoelectric materials. The piezoelectric effect describes the relation between mechanical stress and electrical voltage in solids. It is reversible: applied mechanical stress will generate voltage and applied voltage will change the shape of the solid by a small amount. The behaviour of piezoelectric material can be described [8] by following relationship:

$$\begin{aligned} \boldsymbol{\sigma} &= \mathbf{C}\,\boldsymbol{\varepsilon} - \mathbf{e}^{\mathrm{T}}\,\mathbf{E}\,, \\ \mathbf{D} &= \mathbf{e}\boldsymbol{\varepsilon} + \boldsymbol{\epsilon}\,\mathbf{E}\,, \end{aligned} \tag{1}$$

where $\mathbf{D}$ is the vector of electric flux density, $\boldsymbol{\epsilon}$ is the dielectric permittivity matrix, $\mathbf{e}$ is the piezoelectric coefficient matrix and $\mathbf{E}$ is the electric field vector.

The big advantage of piezoelectric materials is that they respond and may be controlled in real time. As piezoelectric patches can be used for exciting as well as for sensing a structure, shifts of eigenfrequencies of the structure can be recognized with these means. Such shift means that a change of the structure happened. This is the first step for structural health monitoring (SHM) and failure prediction. That may eliminate scheduled inspections and improve efficiency and accuracy of maintenance. Using piezoelectric sensors also means continuous monitoring of structure, therefore it can predict failure before a scheduled inspection.

With knowledge of piezoelectric effect, SHM using piezoelectric patches for exciting and sensing a structure can be applied.

2. SHM of composite materials

Based on previous research with piezoelectric patches on an isotropic aluminium structure [6], composite structures with piezoelectric actuator and piezoelectric sensor were examined. Firstly, three plates were compared, out of which two were with different range of damage already. The undamaged plate was taken as a reference value to the others. During excitation tests major troubles were revealed, resolved and prevented in following experiments. Consequently new undamaged composite plate was investigated and subjected to several impacts. After experiments with unidirectional composite plate, more complex body was examined. A sandwich beam made of two outer composite layers and a foam core was investigated and subjected to several impacts. More sandwich beam bodies were impacted in the same manner to get comparable results.

2.1. Composite plates with different range of damage

Unidirectional long fiber composite plates from experiments realized by Mandys et al. [4] were used. These specimens were made of four layers of unidirectional carbon-epoxy composite with dimensions of 270 mm × 150 mm × 1.15 mm (see Fig. 1). Two plates were with a crack already, created from impacts to the center of the plate. This crack was in direction of the fibers, parallel to edges, intersecting the center of the plate. The lengths of the cracks measured optically were 59 mm and 168.5 mm. As material properties can change in dependency on the production (for example by changing of material base supplier or technological process) they were verified experimentally (Table 1) [5].

In order to evaluate the upcoming results, several impact experiments on the plate with no damage were performed. An impact created oscillation strong enough to last for a period of time sufficient enough to show eigenfrequencies clearly. This is visible on Fig. 2. Delay between

Table 1. Material properties (Young's modulus, shear modulus, Poisson's ratio and density) of composite plate

Material property	E_L [GPa]	E_T [GPa]	G_{LT} [GPa]	ν_{LT} [–]	ρ [kg · m^{-3}]
Value	153.4	7.8	4.5	0.28	1 510

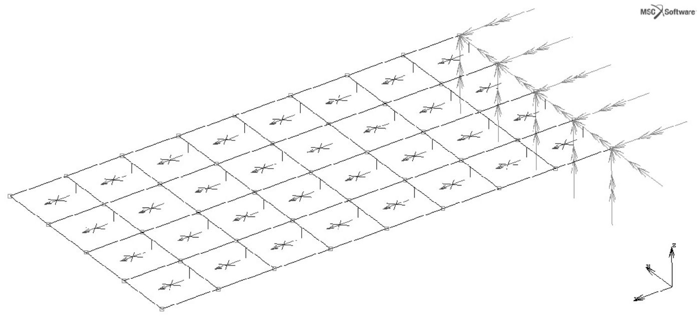

Fig. 1. Finite element model with fiber orientation in direction of arrows in elements

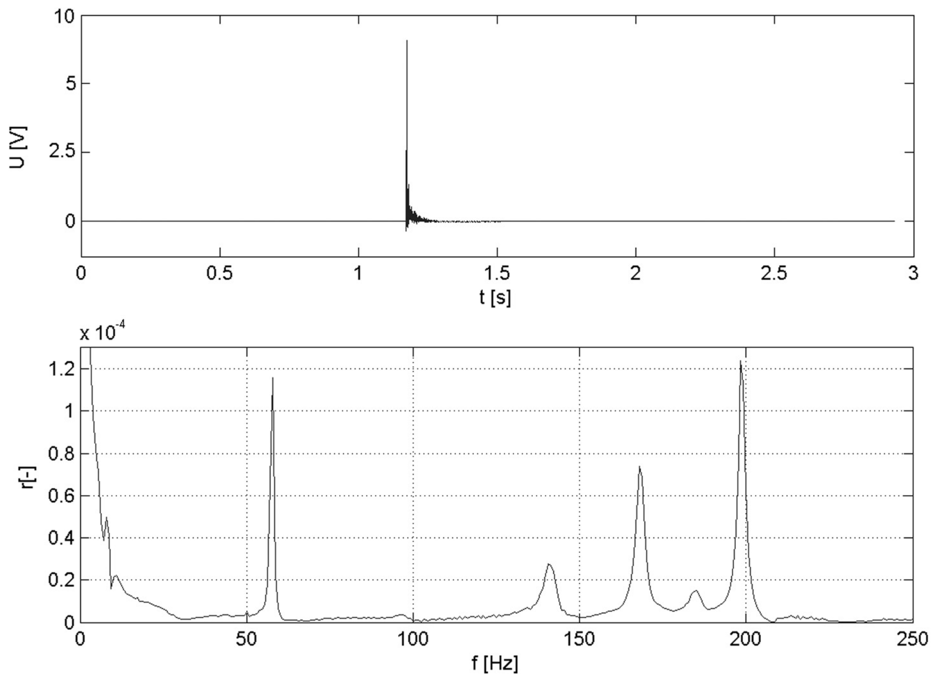

Fig. 2. Excitation with impact

start of experimental measurement and impact itself is visible in the first half of the graph. First part of the figure shows voltage inducted in piezoelectric patch by impact, second part shows eigenfrequency spectrum. The scale of r of the graph in second part is only illustrative, as the excitation force is unknown.

Material properties mentioned in Table 1 were used for creating a finite element models in MSC.Marc. One model of a plate without a failure, second with a failure, that simulated a crack in a damaged plate. These two models corresponded to specimens from experiments in [3, 5]. Results from finite element modelling were compared to results from the impact experiment (compare with Table 2). Values from the experiment and finite element method (FEM) analysis

Table 2. Results from experiment and MSC.Marc for undamaged plate

Frequency	1	2	3	4	5
MSC.Marc [Hz]	59.23	156.4	167.6	200.8	205.6
Experiment [Hz]	57.81	140.6	168.0	185.7	198.4
Difference [%]	2.40	10.10	0.24	7.52	3.50

differ in maximum 10 % in the tracked eigenfrequencies. This can be influenced by imperfection of the impact (double impact) or by variation of material properties after manufacture as well as by attached wires and patches that were neglected in the finite element model. Nevertheless, aim of the impact experiment was not to achieve a perfect match, but to verify, that the sensor and related equipment is connected correctly and able to fulfill its purpose.

The undamaged plate that was used in previous impact experiment was connected into a circuit shown in Fig. 3. The experiment was controlled by a computer, connected to National Instruments CompactDAQ unit with 9263 output module and 9215 input module. The output module converts the digital signal generated to an analog signal with amplitude of 2V. This signal is 50 times amplified by a driver to achieve stronger exciting effect. The amplified signal goes to the actuator glued to the plate. The applied voltage contracts and stretches the piezoelectric patch, which excites the plate. The oscillation is than captured by the second piezoelectric patch. The sensor sends the signal through a charge amplifier to the input module, that converts analog signal **U** to a digital signal. This is saved by the computer. The plate was hanged loose and examined using two piezoelectric patches of the same type P-876.SP1 (Lead Zirconate Titanate PIC 255 material) that were glued with HBM Z70 adhesive. Vibration results in a response r (Eq. (2)). The response r of the piezoelectric patch expresses ratio of voltage amplitude on sensor compared to actuator. The strength of output signal O [V] that is sensed by the sensor is compared to input signal I [V] which is send to excite the actuator. In our case this may be expressed by

$$r = 50\,\frac{O}{I}. \tag{2}$$

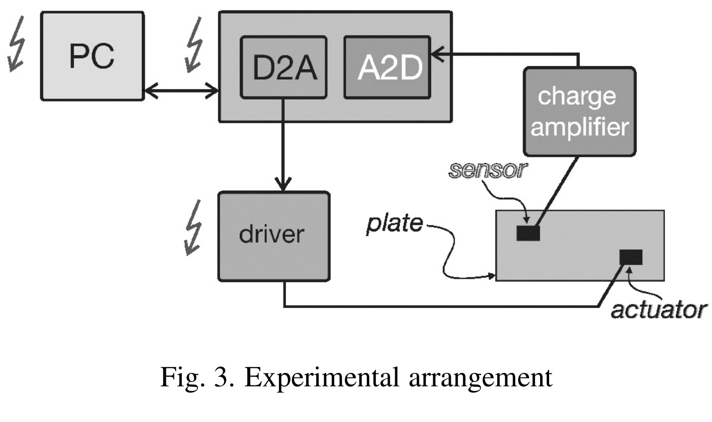

Fig. 3. Experimental arrangement

Both patches were fixed to the same face of the composite plate, symmetrically to the centre of the plate. Series of experiments were carried out. Different types of shielding were put in action, but none of them was sufficient enough. Different approaches were used, but only low accuracy was achieved. Therefore, different approach was chosen – excitation with linear chirp signal. A chirp (or also sweep signal) is a signal in which the frequency increases or decreases with time. In this case an increasing frequency signal was used. All three composite plates with different range of damage were excited with chirp signal from 0 Hz to 5 000 Hz lasting for 10 s with sampling frequency of 51.2 kHz (for input signal as well as for output signal). This resulted in different responses r (Eq. (2)) as can be seen on Fig. 4.

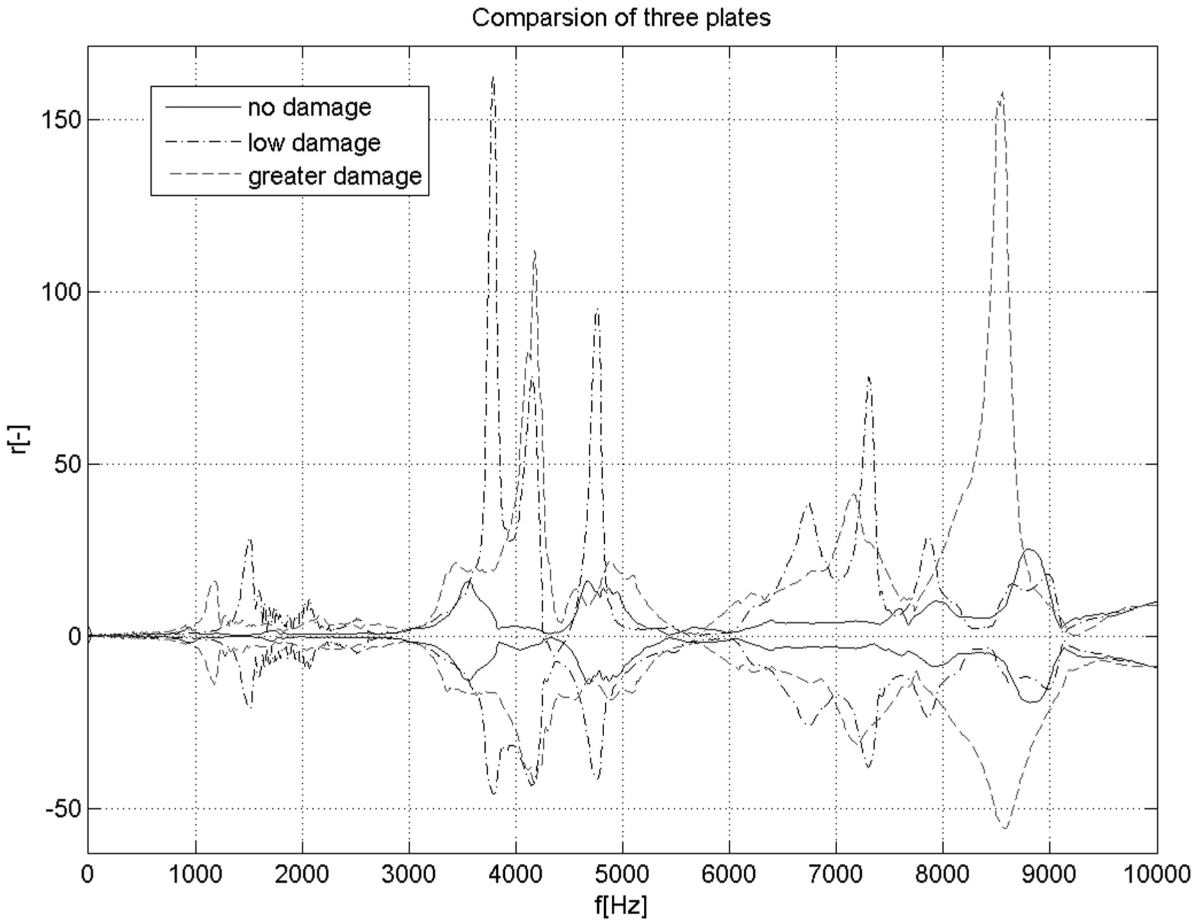

Fig. 4. Dependency of amplitude on frequency for a plate hanged on a tape

After experiments the piezoelectric patches were removed. The glued area was inspected to verify that the piezoelectric patches were glued properly. No problems were found.

Because the sensor was reused, there was a risk, that the attached amplifier will change its position and it will distort the results. The amplifier was therefore fixed into a stable position to the sensor and the same sensor was used in all experiments. Influence on results by using a different equipment was therefore minimalised.

Change of output signal for different plates was evident, but from obtained results it was not clear, how much testing of different specimens influence the results. It was desirable to perform experiment of one comparable specimen, with patches on same location, so that influence of imperfections caused by different specimens would be minimalised.

2.2. Gradually damaged composite plate

Series of impacts were performed on a new unidirectional composite specimen, with measurement of spectrum of eigenfrequencies on undamaged plate and after each impact with chirp signal beginning on 0 Hz and growing up to 5 000 Hz with sampling frequency of 51.2 kHz.

The experimental arrangement was same as in previous case, shown on Fig. 3. Three measurements were performed and recorded to evaluate the results after each impact.

The composite plate was impacted by a 258 g impactor with velocities 1 m/s, 1.5 m/s, 2 m/s, 2.25 m/s, 2.4 m/s, 2.5 m/s, 2.75 m/s, 3 m/s and 3.25 m/s. No significant change was found until the first impact with 3.25 m/s. This was the point, where a visible damage happened. After the first damage, the experiment continued with series of impact with velocity of 3.25 m/s with a growing damage (see Table 3). In total, seven impacts with velocity of 3.25 m/s were performed, until the matrix was damaged along the whole length. Damaged plate was divided into two parts in longitudinal direction and stayed connected only with remaining fibers. Therefore the curve representing spectrum of eigenfrequencies of damaged plate is significantly different from others. This can be seen on detail of spectrum of eigenfrequencies in Fig. 5.

Table 3. Length of crack and selected eigenfrequency

Length of crack [mm]	0	58	100	129	157	204	241	269
Eigenfrequency [Hz]	1 697	1 681	1 674	1 667	1 639	1 607	1 595	1 565

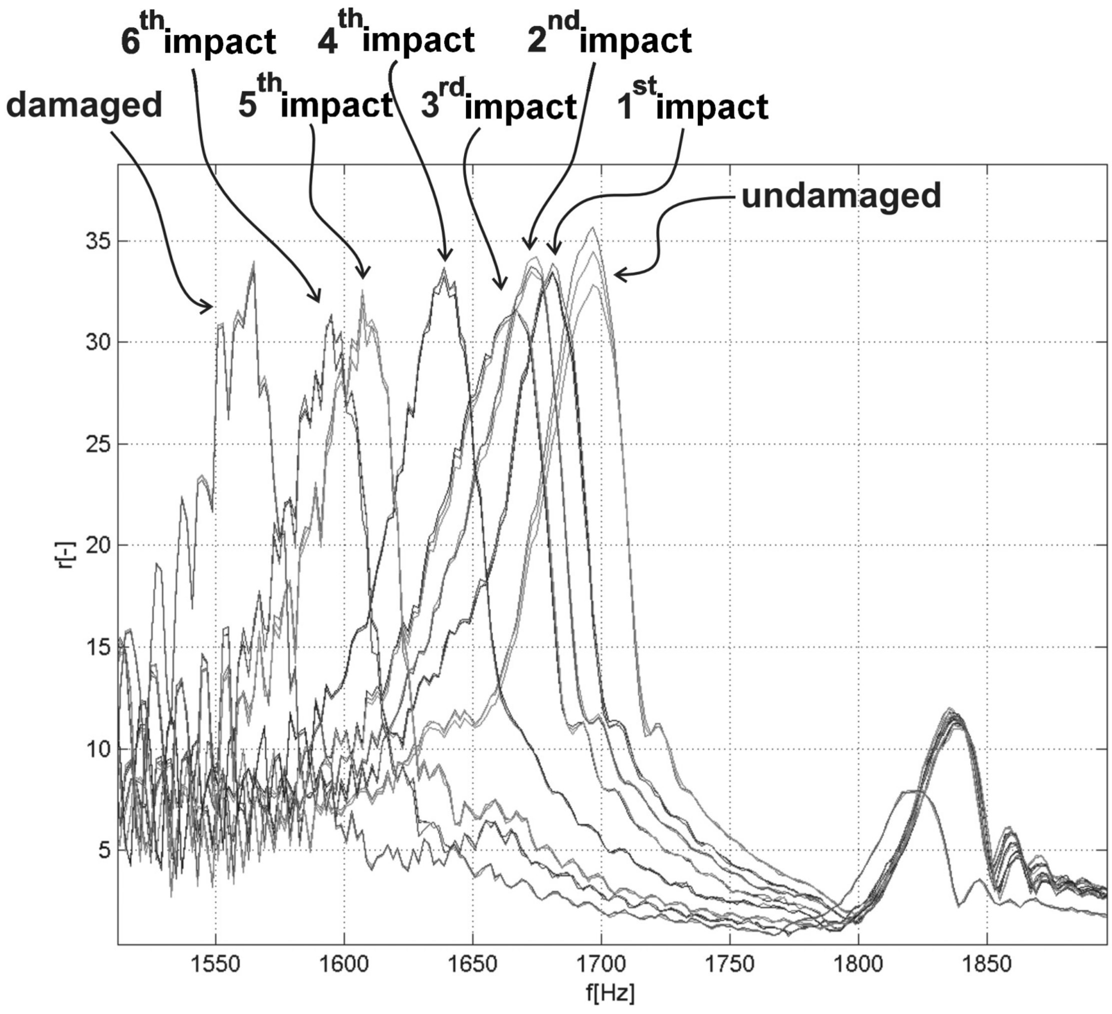

Fig. 5. Detail of shifting eigenfrequencies

Identification of the crack using above mentioned method was possible first when the crack was visible to a human eye. Earlier identification of damage was expected, such as matrix cracking inside the plate. This did not happen, probably because the limit velocity before the unidirectional plate cracks in the whole thickness was exceeded. Nevertheless, identification with described method may be still an advantage in industry, because a failure may be identified earlier than by a regular visual inspection.

2.3. Gradually damaged sandwich beam

Following experiments were focused on a specimen where more different failures may happen – a sandwich beam. Set of sandwich beams (cut out from one sandwich plate made of two outer composite layers and a foam core) was investigated and subjected to several impacts. More bodies were impacted in the same manner to get comparable results. Impacts were performed with growing impact energy. Impactor of 2.1 kg was used, because higher energy impact was desirable. Specimens No. 2, 3, 4 and 5 were investigated under similar conditions. Main difference was in location of piezoelectric actuators and sensors, that was modified to see how the results will be influenced. The sensor and the actuator were glued to the upper (impact) skin of the specimens No. 2, 3 and 4. Additional actuator was glued on the lower skin of the specimen No. 4. Therefore, actuation from skin different to where the sensor was placed, was possible. On specimen No. 5 were both piezopatches glued to lower (non-impact) skin of the beam. Exciting with actuator that was used in previous experiments was not very strong and the response was very weak as the beam had strong damping effect. Another piezoelectric patch (P-876.A12 – also PZT PIC 255 material) was therefore used for exciting the beam. Otherwise the experimental arrangement was same as in previous cases, shown on Fig. 3. Clear shift of eigenfrequencies was found with growing damage, just like in previous cases.

Table 4. Overview of impact energies

Impact No.	1	2	3	4	5	6	7
Energy [J]	5	5	10	15	20	25	30
Height [m]	0.237	0.237	0.474	0.711	0.948	1.185	1.419

All examined specimens showed similar frequency spectra before the impacts (see Fig. 6). During the impact experiments the specimens were not damaged absolutely equally, difference in damage was clear from basic visual inspection. Change of frequency spectra proceeded in comparable manner for all examined specimens (see frequencies from 500 to 2 000 Hz on Fig. 7). How the resulting damage differs may be seen on Fig. 9.

3. Conclusion

Presented research showed that piezoelectric patches can be used for the excitation and measurement of response of an anisotropic structure to detect damage. Real-time method of excitation with chirp signal was used for composites because of strong material dumping. Series of impacts and gradual damage on specimens were performed. After each impact repeated investigation of spectrum of eigenfrequencies was performed.

An unidirectional plate was impacted and a crack appeared for a certain impact energy. A change of the spectrum of eigenfrequencies was consequently found. With a growing crack the eigenfrequency spectrum was changing in the same gradual manner. Deeper research may

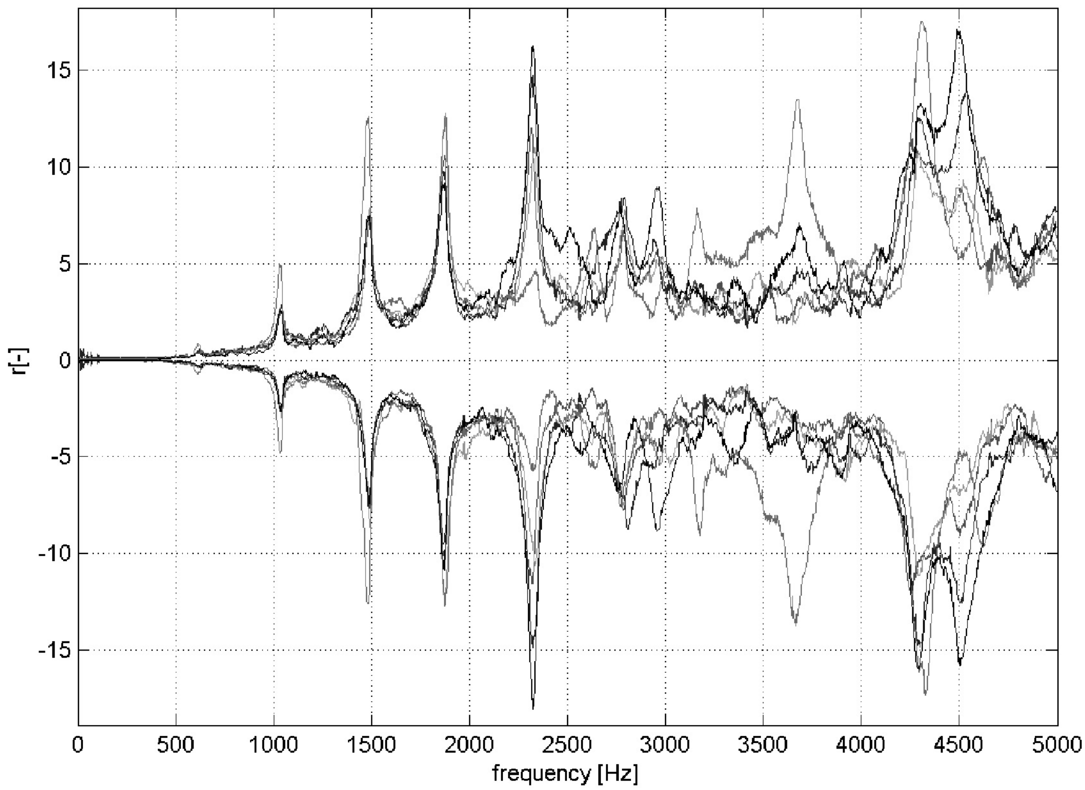

Fig. 6. Excitation with chirp before the impacts – all specimens

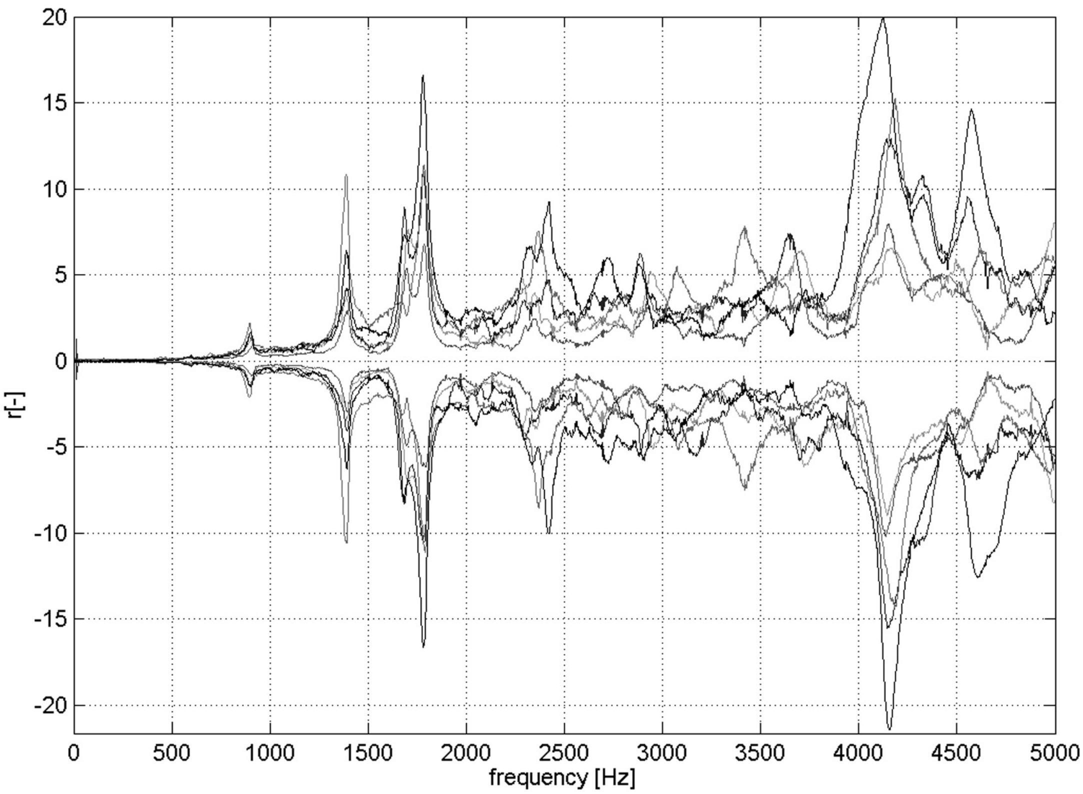

Fig. 7. Excitation with chirp after last impact – all specimens

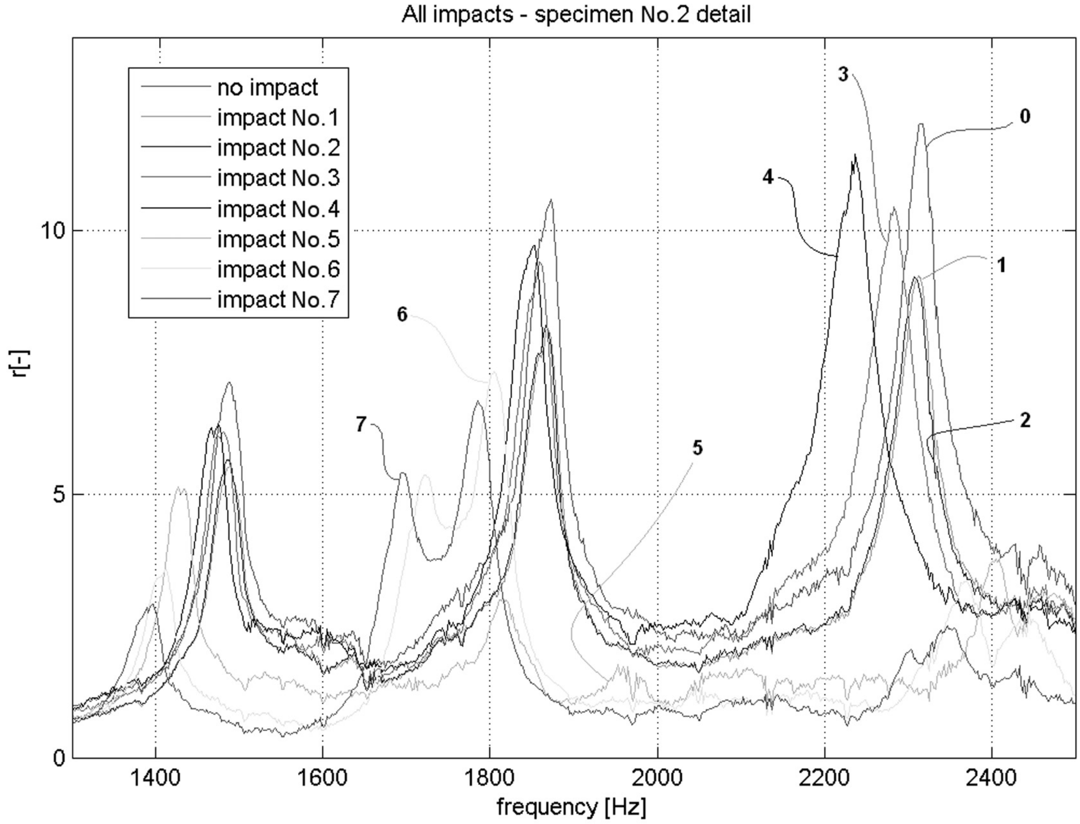

Fig. 8. Excitation after all impacts – detail – specimen No. 2

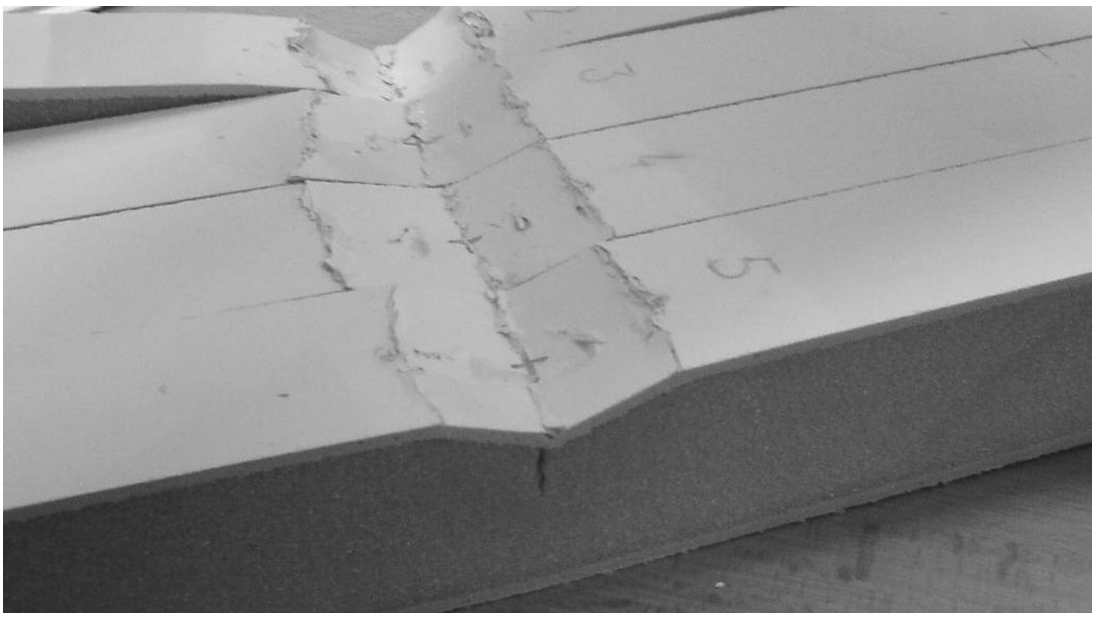

Fig. 9. Impact area on specimens after experiments

validate a possibility to roughly determine the size of the crack according to the shift of the spectrum of eigenfrequencies. This may be than used not only for detecting a damage outside visible area but even more for monitoring of failure development.

Stronger piezoelectric actuator was implemented in case of sandwich beam. Four specimens were examined in comparable manner. The same pair of piezoelectric patches was used on different specimens. Patches were fixed on different locations. All used alternatives were able to reveal the induced damage. Experiments showed gradual change of tracked spectrum of eigenfrequencies with a growing damage, just as it did in previous experiment with the composite plate. The damage was not so easily predictable as in the case of the composite plate, because different types of damage occurred. Nevertheless growth of a damage might be deduced from the shift independently of patches location.

Acknowledgements

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